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FUNCTIONAL DESCRIPTION OF THE CYBERWARE COLOR 3-D DIGITIZER 4020 RGB/PS-D

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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FOR THE COMMANDER

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This report documents the first phase of a 3-D surface scanning system validation study. The study has three phases: (1) component functionality, (2) application as a measurement tool, and (3) comparison to traditional methods for research and design applications. The first phase describes the Cyberware Color 3-D Digitizer, Model 4020 RGB/PS-D used for anthropometric data collection at the Computerized Anthropometric Research and Design (CARD) Laboratory at Wright-Patterson AFB OH. The Cyberware system is described in terms of its system functional and technical specifications. The intent of the first phase is to establish the foundation for performing subsequent scanning system investigation and validation tasks.

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PREFACE

The authors wish to thank Dan Mountjoy and Barbara McQuiston for their assistance in developing the objectives of this study. The authors also wish to acknowledge Pete Marasco for his contributions to defining the scanner optics and laser principles of operation, Mark Wohlslagel for his help with describing the charge coupled devices and Bill Kilpatrick and Patrick Files for their technical editing.

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ABSTRACT

This report documents the first phase of a Three Dimensional (3-D) surface scanning system validation study. The study has three phases: (1) component functionality, (2) application as a measurement tool, and (3) comparison to traditional methods for research and design applications. The first phase describes the Cyberware Color 3-D Digitizer, Model 4020 RGB/PS-D used for anthropometric data collection at the Computerized Anthropometric Research and Design (CARD) Laboratory at Wright-Patterson AFB, OH. The Cyberware system is described in terms of its system functional and technical specifications. The system inputs, outputs, and components are identified, and the system components' principles of operation are described to establish the attributes, capabilities, and limitations of this Cyberware scanning system as a measurement tool. The intent of the first phase is to establish the foundation for performing subsequent scanning system investigation and validation tasks.

INTRODUCTION

An advanced laser digitizing system has been used in the CARD Laboratory at Wright-Patterson AFB since 1987 to collect human anthropometric data on thousands of subjects. In principle, the Cyberware Color 3-D Digitizer 4020 RGB/PS-D scanning system is an accurate tool for measuring the complex curvatures of human subjects. However, few scientific evaluations have been documented to quantify its inherent capabilities as a measurement tool or to assess its superiority over traditional measuring techniques. This study is the first of a three phase effort to scientifically investigate the capabilities of this laser scanning system as a measurement tool and focuses on defining the functional and technical specifications of the system. A firm understanding of the system's design, components, and principles of operation are necessary before subsequent investigations can be pursued.

The scanning system is analyzed in phase one to identify the overall system inputs, outputs, and function and to identify the system components and their principles of operation. The investigation of the system design and operation is to a level of detail necessary to establish a system functional description.

Two additional phases are proposed to continue the Cyberware scanning system investigation. The second phase will investigate the capabilities and limitations of the scanning system as a measurement tool. Areas to be investigated will include: (1) scan volume, (2) accuracy (and repeatability) of the range data, (3) accuracy (and repeatability) of mapping the color data to the range data, (4) effect of color and reflectivity on the range image, (5) effect of color and reflectivity on the color image, and (6) effect of ambient light on the range and color images. The third phase will investigate the capabilities and limitations of the scanned data for use in design applications. This effort will include a comparison of traditional and scanned anthropometric data as well as statistical repeatability of the scans.

Background

The US Air Force has been collecting anthropometric information on military and civilian personnel for nearly sixty years. The anthropometric data is useful for designers of devices, such as personal protective equipment, which interface with the human and for designers of crew stations with which the human interfaces. Early measurements were the traditional type gathered with spreading calipers and measuring tapes to determine widths, breadths, arcs, circumferences, and distances between anatomical landmarks. Measuring objects with these tools does not capture complex shape and curvature information (Robinette & Whitestone, 1992). Three-dimensional (3-D) shape and curvature were inferred from these essentially two-dimensional (2-D) measurements by artists. Figure 1 shows an example of an artist sculpting a face form for an oxygen mask. He only had data describing approximately 30 anatomic landmarks from which to work. The rest of the information was his best interpretation. Not only were the accuracy of these 3-D models questionable, but they were also costly, task specific, and time consuming. Consequently, an improved method of measuring 3-D anthropometric shapes was needed to improve cost efficiency and measurement accuracy.

The need for accurate and complete surface data of an object led to the use of the plane of light laser scanning system. The laser scanning system performs the data measurements by the principle of triangulation similar to some Coordinate Measuring Machines (CMMs). However, the laser scanner differs from CMMs in that it uses optics instead of a mechanical probe to perform the measurements (Sarath, 1991). The lack of physical contact by the laser scanner permits the measurement of soft surfaces and avoids errors due to friction and pressure between the probe and model.

Another advantage of a laser scanning system is its ability to measure an entire object's surface in a relatively short period of time compared to single point of light systems or CMMs. This is extremely important when measuring living subjects which are unable to maintain a static position for extended periods of time. Research has shown that measurement rates greater than 10,000 points per second are required (Addleman & Addleman, 1987). At these high rates, image data can be collected before movement of the subject causes excessive image distortion. To collect image data at this high rate

requires a real-time scan to capture a 3-D object in digital form. The ideal can be thought of as a "3-D Xerox" (Wilder, 1991) that can make a high resolution surface measurement of a living subject, such as the human head. An instrument developed for the purpose of rapid surface scanning and image data collection is the Cyberware 4020/PS. This Cyberware scanning system is capable of digitizing approximately 250,000 points on the surface of the head, face, and shoulders in about 17 seconds. The level of resolution achieved is approximately 1 mm. This is a tremendous increase from the few traditional landmark points previously used to create 3-D design models.

The CARD Laboratory first purchased the Cyberware 4020/PS in 1986. Several upgrades have been installed to bring the system to the current 4020 RGB/PS-D configuration. Since 1988, 3-D data have been collected on more than 1000 heads and faces (Blackwell & Robinette, 1993; Robinette & Whitestone, 1992; Robinette & Whitestone, 1994). The database is continually updated as new subjects are constantly being scanned. The data collected from these scans serve as a valuable resource to human-system interface designers in various fields of application.

The initial scanning system was developed to create realistic looking 3-D models for artists and the entertainment industry. Artists used the scanner to create personal portrait sculptures. The 3-D scan data could be manipulated, magnified, and/or miniaturized and then used to develop the molds to form the sculpture. The resulting sculptures were then finished by hand to create the final form. Further utilization of the technology by video specialists produced animation and special effects requiring shapes that previously had been difficult to create. Video production has been incorporated into several movies: The Abyss, Nightmare on Elm Street, Robocop II, Star Trek IV, and Terminator 2 (Wilder, 1991).

While the scans were certainly very realistic, this did not guarantee that they were accurate enough for other purposes. For example, measurement accuracy is a critical concern in the design of equipment involving close contact with the human (e.g., personal protective equipment, optical devices, and gas masks). Constrained cockpits, increasing operator task performance, and operator movement restrictions all require even more accurate definition of the human equipment interface. To make the scanning system suitable as a measuring device for such applications, measurement of the system's accuracy and a method to dimensionally calibrate the system were required. Initially, Deason measured

the system's accuracy to be about $\pm$ 3 mm, and he devised a calibration method. After calibration, the accuracy was improved to about $\pm$ 1 mm (Deason & Ward, 1989). With this level of accuracy the scanning system was considered a useful tool for many applications.

Landmarking and the Need for Color

It was initially thought that a $\pm$ 1 mm accuracy was necessary in order to detect pre-marked anatomic landmarks with the scanning system. The first method to mark landmarks for scanning was to place steel pellets or bb's over the anatomical location. These did not prove effective as they were difficult to attach, and the subjects continually displaced them. Also, it was difficult to digitize enough detail to identify the landmarks properly. An alternative landmarking method was devised to mark the anatomical locations with dark green fuzzy dots. These essentially left a void spot in the data which, generally, were easy to detect except when in close proximity to other surfaces that did not directionally scatter light, such as hair. On the other hand, the voids from the green fuzzy dots required the data to be "filled" after the landmarks were detected and located in order to smoothly represent the scanned surface. The addition of a color camera mapped to the geometric information made it possible to use color dots which did not cause voids. It also led to the development of methods for automating the extraction of landmarks which greatly speed up the post-scanning data processing.

Applications

These advancements have improved the potential to use laser scanning technology in engineering applications. For example, the capability of scanning an object and preparing the file for computer-aided design and manufacturing (CAD/CAM) has increased manufacturing efficiency by allowing design modifications in minutes instead of hours or even days. Also, golf club manufacturers have been able to scan the masters of club heads to preserve the shape that artists have taken years to create (McMillan,

1989). Furthermore, NASA researchers have utilized a Cyberware 3-D surface scanner to rapidly measure models used in computational fluid dynamics (CFD) simulations (Merriam, 1992).

Another profession using laser scanning technology is the medical field. Medical researchers and physicians have incorporated the 3-D surface scanning technology in reconstructive and cosmetic surgical plans (Vannier, 1991). Other areas of application include prosthetics and orthotics (Houston et al., 1993; Engsberg et al., 1992), optimizing the size of hearing aids (Wohlers, 1992), and as a teaching tool for dentists in Denmark (Wilder, 1991). Dr. William Sadler of the University of Illinois has also developed a method to implement aging algorithms with the scans to create facial prosthetics for children (Mahoney, 1990) and to aid in the search for missing children (Wilder, 1991).

The variety of possible applications can also expose limitations in the scanning technology. This variety, combined with new technology advances, make Cyberware scanners a dynamic series rather than a single static system. It is important, therefore, to document the properties of the particular scanner in use, particularly in terms of its function.

SYSTEM DESCRIPTION

System Overview

The Cyberware Digitizer 4020 RGB/PS (Addleman & Addleman, 1987; Addleman & Addleman, 1988) uses a Helium-Neon laser that is diverged through stationary optics into a vertical plane of light. The laser light and the cool white fluorescent auxiliary light sources illuminate the surface of the object being scanned, and this light is directionally scattered by the object through a series of mirrors and prisms to two cameras, which digitize the images. The cameras record the object contour and color information by converting the optical signals into digital data. The digitized data is synchronized by electronics and incorporated into a data file on a computer workstation. The ECHO software, developed by Cyberware, resamples the data, converts the information to cylindrical coordinates, and maps the range and color files together. Detailed descriptions of the Cyberware laser scanner equipment and operation are provided in the following sections. Figure 2 is a diagram showing the basic system operation, configuration, and optical path.

System Components and Upgrades

Advances in 3-D laser scanning technology have brought about periodic upgrades to the Cyberware 4020 system. The following is a brief description of the various system modifications leading up to the current RGB/PS-D configuration:

Revision B

The 4020/PS Revision A system, distinguished by a Vidicon video camera and Hewlett Packard (HP) computer, was shipped to EG&G, Idaho, for evaluation testing in May 1987. A bandpass interference filter and anamorphic lens modification were installed by Cyberware while the scanner was

at EG&G, Idaho, resulting in revision B of the scanner head. The inclusion of the new optics required the system to be re-calibrated in 1987. The system was shipped to Wright-Patterson AFB in late 1987.

Revision C

The system was shipped from Wright-Patterson AFB in December 1989 to Cyberware (Monterey, CA), where the video camera was replaced with a range charge coupled device (CCD) camera as revision C. Additional modifications included system re-calibration, an SGI interface and software, and an ethernet controller. An extended vertical slide was also installed at this time.

Revision D

The color CCD camera and auxiliary light bar were installed on site at the CARD Laboratory in December 1990. This modification resulted in revision D of the scanner head.

Cable Upgrade

The latest modification to the system was the installation of a new cable system in May 1994. This modification provides a longer, improved ribbon cable and guides to prevent accidental disconnect as the scanner head rotates around the platform.

ECHO Software Upgrade

The ECHO software was updated in September 1995 by Cyberware. Previously, the software created data files with 256 latitudes. The current software creates files with 512 latitudes. Consequently, this report has been written with reference to the current data files that contain 512 latitudes. All previous files obtained at the CARD Laboratory have 256 latitudes.

These upgrades have developed the system, owned by the CARD Laboratory, into the current 4020 RGB/PS-D configuration. An explanation of the model nomenclature is provided below:

4020	- a cylindrical scanning volume of approximately 40 cm high with 20 cm radius
RGB	- color camera capability (red, green, blue)
PS	- motion platform
D	- revision level

Sub-Systems

The system component identification is divided into three main sub-systems: optics, electronics, and software (see figure 2). Each subsystem represents a specific class of functions required to scan an object and convert the optical images to digital format. The optics sub-system includes the light sources which illuminate the subject and the path of the light which is scattered from the subject to the range and color cameras and recorded as an image. The electronics sub-system includes the range camera, the color camera, and the electronics needed to digitize the optical images. The software sub-system includes resampling and cylindrical coordinate calibration tables to output the range and color image files. A separate section is provided to address two additional system components: the motion platform and auxiliary lights.

Optics

Light Source: A laser beam is a near-parallel, monochromatic, and coherent beam of light created by exciting atoms within a resonate optical device. These attributes allow the laser to create a precise line of light without the fuzzy edges characteristic of incandescent light sources. The beam of laser light is spread by cylindrical concave lenses into a 40 cm vertical plane of light which illuminates the surface of the object being scanned. As the laser draws a profile line on the object, light is scattered

to the range camera, which captures 484 points per profile line. Five hundred and twelve successive profile lines are captured to define the object. The 484 points along each of the 512 profile lines are eventually resampled to 512 points per line.

The laser used by Cyberware is a Melles Griot, Class IIIb, 4 mW Helium Neon laser with a wavelength of 632.8 nm and a beam diameter of 0.8 mm. The plane of light is generated by passing the laser beam through two plano-cylindrical negative lenses of uncoated BK glass. The first lens, mounted on the laser head, has a paraxial focal length of -6.53 mm $\pm$ 5%, and the second lens, located approximately 71 mm from the first lens, has a paraxial focal length of -25.4 mm $\pm$ 5%. At the aperture exit, where the beam leaves the enclosure, it is dispersed to a length of 215 mm with a width of 1 mm. The beam reaches a length of approximately 350 mm in the region of the subject. The beam power range at the aperture exit is 80 μW maximum to 25 μW minimum per 7 mm diameter. This was measured with a 7 mm diameter test aperture stop on a photometer (Addleman, 1986). A diameter of 7 mm is the size used for eye safety testing since it is the typical size of a dilated pupil. An electronic timer limits the time the laser is on to 30 $\pm$ 1 seconds for each exposure cycle. See Appendix A for the Melles Griot technical specification sheet.

Subject: The subject or object to be scanned is placed in the center of the scanner arm field of rotation. Not all of the surfaces of the subject will be well captured by the scanning system, and areas of missing image data can occur. The areas not well captured are called void areas. When scanning the human head, the amount of void data compared to captured data is usually insignificant (Sarath, 1991). Voids most commonly occur when little of the incident laser light scatters towards the range camera. This can occur due to the shape or the texture of the surface being scanned. At locations on the object which have a nearly horizontal surface, little or no laser light falls on the surface and even less is scattered in the direction of the range camera. These nearly horizontal shapes account for the presence of voids on top of the head and under the chin. Voids also occur when scanning an object with a fuzzy surface texture. In this instance, the incident laser light falls on the surface, but is scattered randomly without prominent scattering in any one direction. Therefore, little of the incident laser light is scattered

in the direction of the range camera. This accounts for voids introduced in the data with the green fuzzy dots used in an early landmarking method, as described in the introduction. It also accounts for the typical voids in the region of the subject's hair. To minimize voids from hair, subjects can wear a skin-tight bald cap to cover their hair if the cranial shape of the subject is desired. Also, their hair can be covered with powder if a scan including the subject's hair is desired.

Several methods are available to obtain this missing image information caused by voids. One method is to acquire multiple scans at different angles and to register them together with landmarks. This allows surfaces that are horizontal in one scan to possibly be non-horizontal in another scan and thus be visualized by the range camera, but the registration poses problems. Another method is to use software that interpolates the missing information based on neighboring points which, in effect, "fills" the voids.

Mirrors: As previously described, the laser digitizer projects laser light onto the surface of an object. The laser light is then scattered towards the cameras. The paths of light from the laser to the object and from the object to the cameras form a triangle. The angle of the triangle at the surface of the object is called the probing angle. The probing angle represents a design trade-off of accuracy and resolution (Wohlers, 1992). A large probing angle allows for highly accurate measurements, but the system cannot "see" into deep concavities, undercuts or openings, and resolution suffers. On the other hand, a small probing angle allows for better coverage of the surface or resolution, but this small angle propagates error through the triangulation calculations to result in less accurate measurements. The 4020 RGB/PS-D utilizes a probing angle of approximately 30 degrees, providing a good balance between accuracy and resolution. The Cyberware scanner utilizes multiple mirrors which project two different images from different angles to the range camera (see figure 2). The purpose of generating two images is to provide information from another view in the event one view is obstructed (e.g., the sides of the nose).

Beam Splitter: These two different images, created by the mirrors as described above, are combined by the beam splitter (see figure 2). This component is a mirror with a thin-film optical coating

which permits the light to pass from one side and to be reflected from the other side. The two images are focused on top of each other and form a single image on the range camera CCD array.

Laser Line Filter: The laser line filter is located in front of the range camera and filters out most visible light wavelengths, except that of red light at a wavelength of 632.8 nm. The filter is needed since the light generated by the cool white fluorescent lamps, which illuminate the subject for the color camera, combines with the red laser light. The filter is able to reject much of the fluorescent light because cool white fluorescent light does not contain much light at 632.8 nm. The spectrum from a cool white fluorescent light source is skewed towards the blue portion of the visible spectrum, compared to sunlight or incandescent light. Since the filter allows red light at 632.8 nm from any source to pass through to the range camera, careful attention is needed to minimize the amount of red light at this wavelength from light sources other than the laser. Therefore, while scanning, much effort is made to maximally attenuate all sources of sunlight, incandescent light, and light from intense sources such as bare filaments or even bare fluorescent bulbs near the scanner.

Anamorphic Lens: An anamorphic lens is a lens that has different magnifications in the horizontal and vertical directions. A good example is the use of an anamorphic lens to convert the wide screen of a motion picture to a narrow film image. The anamorphic lens used by the Cyberware scanner has greater magnification in the vertical direction than the horizontal direction, allowing for the sensing surface of the range camera CCD to be better utilized. Figure 3 illustrates how the anamorphic lens "sizes" the scattered image to project onto the range camera CCD array. The anamorphic lens focuses the directionally scattered laser light from an approximately 40 cm high by 12 cm wide region onto a portion of the range camera CCD sensing area having approximate dimensions of 4.8 mm high by 3.4 mm wide.

Electronics

The electronics section of the Cyberware scanner includes the cameras and electronics which convert the optical signal received by the camera sensors into digital format for data storage and manipulation. The following paragraphs describe in detail the various components comprising the scanner electronics.

The sensors consist of two CCD cameras, a range camera and a color camera. The range camera incorporates a CCD "which acts as an electronic eye" (Merriam, 1992) to digitize the captured image. The color CCD camera captures surface colors and markings to create a red, green, and blue (RGB) data file. The CCD chips used in these cameras are of a higher grade than those used for video camera signals.

Range Camera: 3-D laser digitizers commonly use a CCD camera to record the points illuminated by the laser beam. As described earlier, laser light from the object surface is scattered to the range CCD camera where the optical signal is converted into a digital format. The camera field of view is physically aligned with the light path coming through the beam splitter, but the effective field of view is along a path between the mirrors and the table axis or scanner arm center of rotation (Addleman & Addleman, 1987). The following paragraphs describe the range CCD camera in greater detail. Appendix B contains the CCD technical specifications.

The Cyberware 4020 PS-D uses a Texas Instruments TC245 CCD Image Sensor. This image sensor is a frame-transfer CCD configured into 244 horizontal rows consisting of 786 elements in each row. With interlacing, as described below, the total size of the resulting digitized image is 488 rows x 786 columns. However, the actual CCD sensing area only consists of 242 horizontal rows (without interlacing) of 755 active elements (see figure 4). The remaining columns of elements are shielded from incident light and provide a dark reference used to restore video black levels. The remaining two rows of elements between the image sensing and image storage areas serve as a barrier to prevent charge leakage into the image storage area (see figure 4).

Not all of the 755 active elements are used by the Cyberware scanner. Only 405 of the 755 active elements are used. These 405 elements span 3.4 mm of the CCD array, as described in the anamorphic lens section of the optics sub-system description. The mapping is from 3-D space of 40 cm high x 12 cm wide to CCD array dimensions of 4.8 mm high x 3.4 mm wide with an image 484 pixels high x 405 pixels wide. Therefore, pixels on the CCD array are approximately 9.9 µm high x 8.4 µm wide.

Each element is created by a pair of gate electrodes very close to the surface of the silicon, and is capable of storing a charge packet (a finite amount of electrical charge). By placing the charge elements next to each other, the charge packets can be moved from one storage element to the next by raising and lowering the voltage on the gate electrodes in a particular sequence. This packet transfer is very efficient, allowing one packet to undergo as many as one thousand transfers without being significantly attenuated. The charge in each packet is unique, and a line of charge packets can be treated as analog information.

In the case of the Cyberware scanner, each image the CCD processes represents a 2-D image with the vertical dimension representing the vertical location on the object, and the horizontal dimension representing the radius of the object. As the radius (from the scanner arm's center of rotation) of the object changes, the CCD sees the scattered line of laser light at a different horizontal position in the CCD array. As each row is read from the CCD array, a peak detector (as described in the Electronic Digitizer section below) is used to find the point of greatest illumination on that line. This is the point where the horizontal center of the laser light is illuminating the object. The horizontal location of this peak in the CCD array represents the scanned object's radius for the latitude represented by the particular row of the CCD array processed by the peak detector.

The CCD sensing area is designed to operate in an interlace mode by electronically displacing the image sensing elements in alternate horizontal rows by one half the distance between rows during the charge integration period. This process has the effect of increasing the vertical resolution by a factor of two. Essentially, the interlacing allows a 484 pixel vertical image to be generated from the 242 vertical active array elements. Each array row represents a different latitude on the object; so, as the image is

read from the CCD array, a radius value is determined for each latitude (see figure 5). This process is repeated 512 times as the scanner rotates around the object, resulting in 512 longitudes.

Color Camera: The color camera upgrade (revision D) was added to the system in late 1990. Previous to this date, surface information was displayed in shades of gray from a black and white camera.

The image that the color camera receives travels on a separate optical path (see figure 2). The optical path is displaced horizontally seven degrees from the laser line so that the resulting image is not in shades of red from illumination of the surface by the laser. The optical path to the color camera is simpler than to the range camera and consists of only one mirror, a regular lens, and no beam splitter. The color camera signal is synchronized through the same electronics that serve the range camera, and the color camera uses the same type of CCD chip as the range camera. The main difference in the color CCD chip is that every element of the CCD array includes either a red, green or blue filter allowing the intensity of either red, green, or blue light to be measured by that element. Effectively, these filters break up polychromatic light into three monochromatic components that can be reassembled later to produce a color image. The filters are arranged horizontally in the order red, green, and blue, and each RGB triplet corresponds to one colored pixel. Only a single RGB triplet (three elements) along each of the 484 interlaced rows on the CCD chip are used by the Cyberware scanner for each of 512 longitudes in which data is collected as the scanner rotates around the object. Therefore, three color values (red, green, and blue) are generated for each corresponding range data point. Known geometry is used to determine which color pixel corresponds to each range data point.

Electronic Digitizer: The electronic digitizing hardware translates the analog signals generated by the range CCD into digital format. This hardware is one of the unique features of the Cyberware digitizer and allows fast digitization "on the fly." As the analog signals are read from the CCD chip, the digitizer chooses which of the 405 active elements from each row represents the radius value at that location. Therefore, only one value for each of the 484 digitized points along each of 512 longitudes is required to be sent along a serial data stream, rather than having to send a whole 488x786 CCD frame

across a bus for each of 512 longitudes. Consequently, the Cyberware system can digitize 14,500 points per second (Merriam, 1992), which can be calculated from 484 points per longitude times 512 longitudes, all in 17 seconds. The electronic measurements are encoded as binary data and passed to a digital computer for storage, analysis and other processing (Addleman & Addleman, 1987). Each range data point consists of two bytes of data, and the corresponding color value consists of three bytes of data.

See the electronic digitizer flow diagram in figure 6 for more detail of the box labeled Electronic Digitizer on figure 2. The following quotes are directly from Cyberware's 1987 patent (Addleman & Addleman, 1987), which described a system with a video range camera. The change to a CCD range camera in the Cyberware 4020/PS scanner (revision C) does not significantly change the explanation of the electronic digitizer circuitry.

"The video signal outputs of the video camera sensor have a wide range of amplitude and are frequently asymmetrical due to variations in the reflectivity and slope of the subject surface. If a high accuracy measurement of the radius is to be achieved, special treatment of the camera video is required. For this function an amplitude insensitive trigger circuit is used. The camera video is divided into two equal amplitude parts, one of which is delayed and then applied to one input of a high speed voltage comparator. The sum of the undelayed video and an adjustable bias signal is applied to the other input. The comparator will provide an output whenever the amplitude of the delayed signal exceeds that of the undelayed signal. The comparator output is one-half of the delay time later than the true value. The bias adjustment adjusts the two signals relative to one another so that sensitivity can be set above system noise. The output of the amplitude insensitive trigger enables the latch causing the counter value to be stored" (Addleman & Addleman, 1987). The process continues while the scanner rotates one full turn. "Frame synchronization data can be stored in the computer memory by reserving the highest value radius reading for that purpose and storing it immediately preceding or following the data for each frame" (Addleman & Addleman, 1987).

"An electronic circuit is used for controlling the video camera sensor and processing the camera output. All operations are timed by a clock. During each horizontal sweep an up-down counter counts down from maximum at the beginning of the sweep to zero at the center or table axis image position and

then back up to maximum at the horizontal sweep termination. A coincidence between the counter value and a video response from the contour line yields a counter value proportional to the radius of that surface point of the subject. With this single field, the point coordinate along the axis of the subject rotation is proportional to the vertical deflection or vertical count line. The remaining coordinate is directly related to the rotational position of the subject and can be derived from the sequential frame position. It is not necessary to synchronize the table rotation as long as its velocity is constant and the precise start and end of one revolution is known" (Addleman & Addleman, 1987).

"A method is provided for accurate measurement of the contour image position on the sensor by use of an amplitude insensitive detector along with digital counting and synchronization circuits. The digital computer receives data from all contours. Data is collected in cylindrical coordinate form. To maximize data handling speed the radius data is packed into the word size of the computer. This word of data is then passed to the computer which stores it in the computer's random access memory" (Addleman & Addleman, 1987).

Software

The ECHO software supports acquisition, processing, and output of the scan data, including manipulation and reproduction in both the wire frame and solid form. The ECHO software uses angles of light reflection and triangulation to calculate the object coordinate data. The object coordinate data, along with indexing data, are stored sequentially in the computer's memory (Addleman & Addleman, 1987).

The Cyberware system utilizes a cylindrical coordinate system, as illustrated in figure 7. The theoretical scanning volume is a cylinder 40 cm high with a 20 cm radius (40 cm diameter). As previously described, there are 484 numbers read from the CCD array that correspond to the radius values of 484 points scanned down each profile line. These 484 numbers for each profile line are sent over the ethernet interface to the ECHO Software, as depicted in figure 6. Due to optical distortions, the 484 points are not equally spaced. These points are resampled to create a scan data file such that the

points are equally spaced vertically and horizontally in the cylindrical coordinate system. Each profile line is currently resampled to 512 equally spaced points.

The ECHO Software creates the range data file, which consists of only radius values. The other two dimensions, latitude and longitude (or height, z, and angular separation, θ), are implicit from the location of the radius value in the data array (see figure 8). Configuration tables used for these conversions were developed by Cyberware through calibration during scanner production and during re-calibration in December 1989, when the CCD camera was installed for the revision C upgrade.

Additional Components

Motion Platform: The motion platform version of the 4020 moves the scanner head in a continuous path, 360 degrees around the object, as the subject sits still. The motor drive is a Superior Electric Slo-Syn synchronous/stepping motor type M092-FC09, with a step rating of 200 steps per 360 degrees. Step motors are devices which position loads by operating in discrete increments or steps and are capable of very precise positioning without feedback. The motor is connected to a gearbox housing that drives a single belt to rotate the motion platform. The belt tension can be adjusted to ensure proper scanner head rotation. The motion platform system uses lubricated-for-life ball bearings and is a relatively maintenance free system. Appendix C contains the technical specification sheet for the drive motor.

Auxiliary Light Bar: With the color camera upgrade, lighting became an issue due to shadows. An auxiliary fluorescent light bar was installed to provide adequate lighting under the chin and at the top of the head. A cool white fluorescent light is used since it only includes a minimal amount of red light, having the same wavelength as the laser light (632.8 nm). Appendix D contains the auxiliary light bar technical specification sheet.

FUTURE WORK

The future in 3-D anthropometric surface scanning is full-body scanning. Full-body scanning will present additional challenges in data formatting for storage, hidden areas, stability, and body positioning, etc.

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GLOSSARY OF TERMS

2-D	Two Dimensional
3-D	Three Dimensional
AFB	Air Force Base
CA	California
CAD/CAM	Computer Aided Design/Computer Aided Manufacturing
CARD	Computerized Anthropometric Research and Design
CCD	Charge Coupled Device
CFD	Computational Fluid Dynamics
cm	centimeter
CMM	Coordinate Measuring Machine
HP	Hewlett Packard
mm	millimeter
mW	milliWatt
NASA	National Aeronautics & Space Administration
nm	nanometer
r	Radius coordinate in cylindrical system
RGB/PS-D	Red Green Blue/Motion Platform - Version D
SGI	Silicon Graphics, Inc.
US	United States
z	Height coordinate in cylindrical coordinate system
μm	micrometer or micron
μW	microWatt
θ	Rotation angle coordinate in cylindrical coordinate system

APPENDIX A

Laser Technical Specification

Helium Neon Cylindrical Head Laser

Product Number	05 LHR 141
Min CW Power Output at 632.8 nm TEMoo	4 mW
Beam Diameter @ $1/e^2$	0.80 mm
Beam Divergence	1 mrad, full
Longitudinal Mode Spacing	438 MHz
Weight	0.56 Kg
Operating Current Nominal	6.5 mA
Operating Voltage ± 100	2390 VDC
CDRH Class	IIIb
Recommended Power Supply	05LPL902-065

APPENDIX B

Charge Coupled Device Technical Specification

June 1990

786 x 488 Pixel CCD Image Sensor

Product Number	TC245
Image Area Diagonal	8 mm
Active elements in Image Sensing Area	755(H) x 242(V)
Dynamic Range	Greater than 70 dB
Operational Temperature Range	-10^0 C to 45^0C
CCD Video Output Signal ±10 mV	50 mV

Additional Characteristics

Advanced On-Chip Signal Processing

Low Dark Current

Electron-Hole Recombination Antiblooming

High Sensitivity

High Photo-response Uniformity

High Blue Response

Single Phase Clocking

APPENDIX C

Motion Platform Motor Technical Specification

Motor Type	M092-FC09
Connections	6 Leads
Typical Time for a Single Step (ms)	3.9

Unipolar Configuration

Nominal DC Volts	2.5
Rated Amperes per Winding	4.6
Nominal Resistance per Winding (25 C) ohms	0.55
Nominal Inductance per Phase (milliHenrys)	2.76
Minimum Holding Torque 20 ON	300
Minimum Holding Torque 10 ON	180

Series Connection

Volts	3.6
Amperes	3.25
R	1.1
L	11.04
Minimum Holding Torque 20 ON	370
Minimum Holding Torque 10 ON	225

APPENDIX D

Auxiliary Light Bar Technical Specification

Bulb Size	15 W Cool White Fluorescent
	12 - 20" Long
Lower Fixture	8" - 15" Vertical Adjustment
	0 - 60° Upward Tilt Adjustment
	7" Fore/Aft Adjustment
Upper Fixture	8" - 15" Vertical Adjustment
	0 - 60° Downward Tilt Adjustment
	7" Fore/Aft Adjustment
Total Weight	Less than 10 lbs

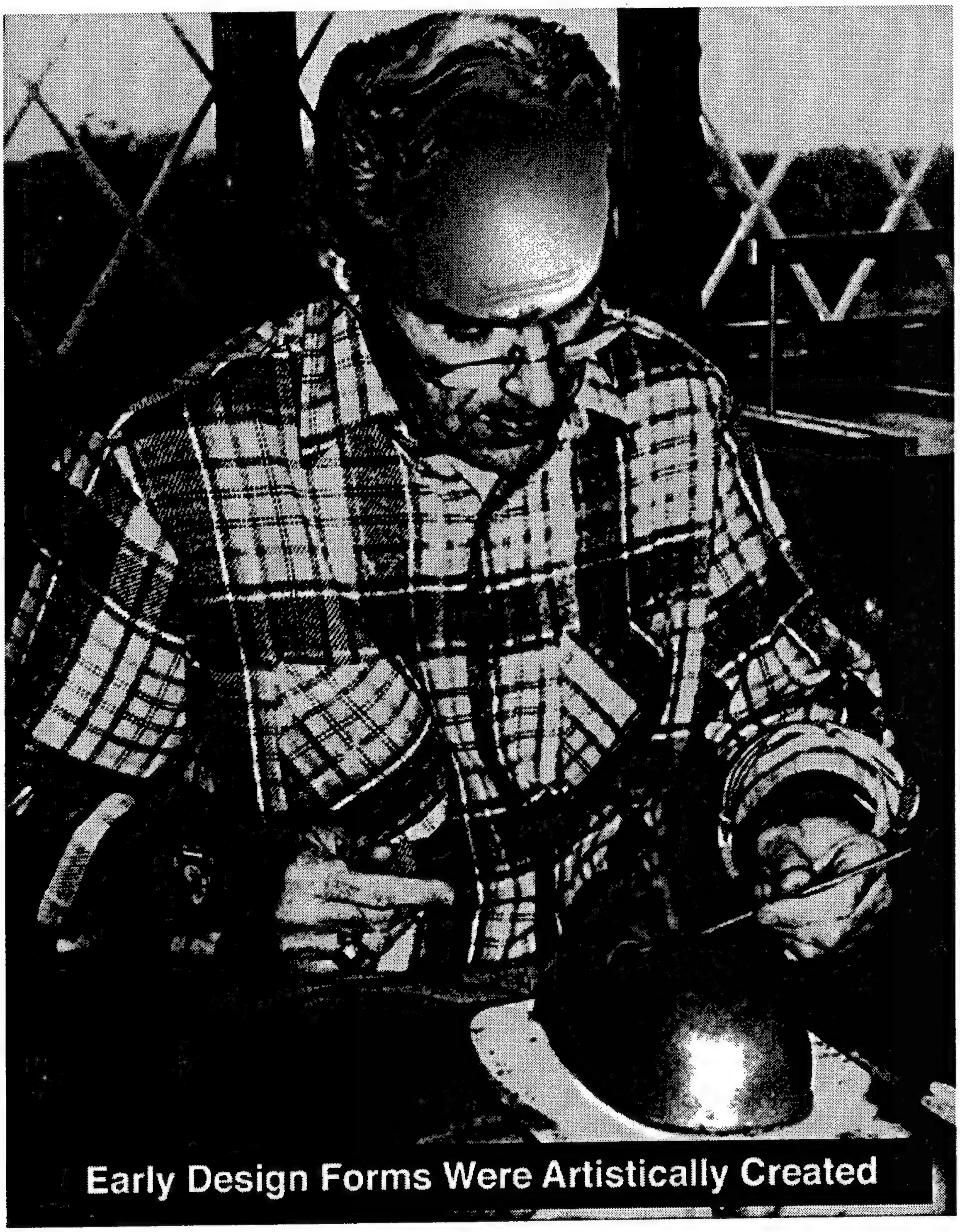


Figure 1, Hand Sculpture of Face Form

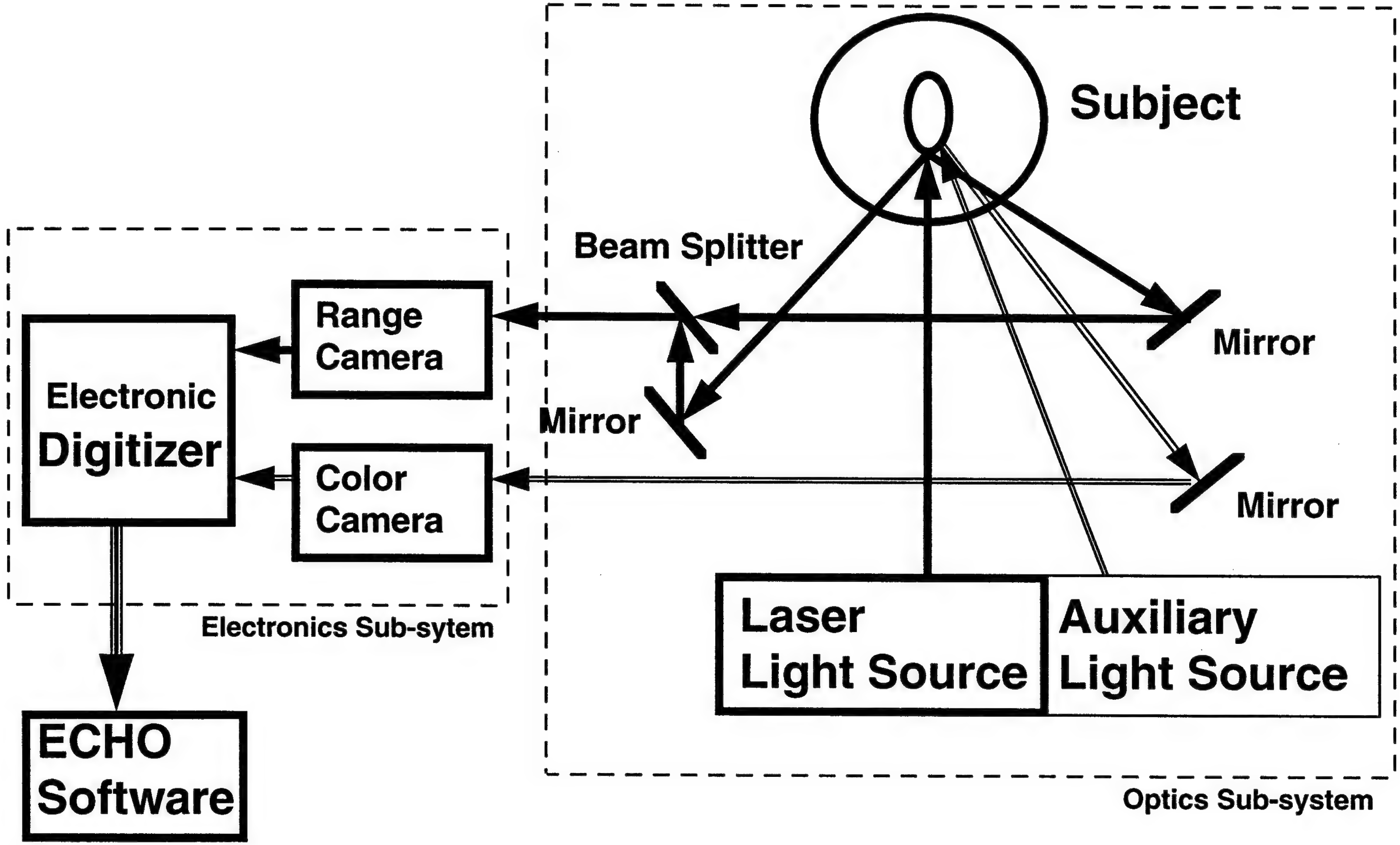


Figure 2, Cyberware 4020 RGB/PS-D Configuration

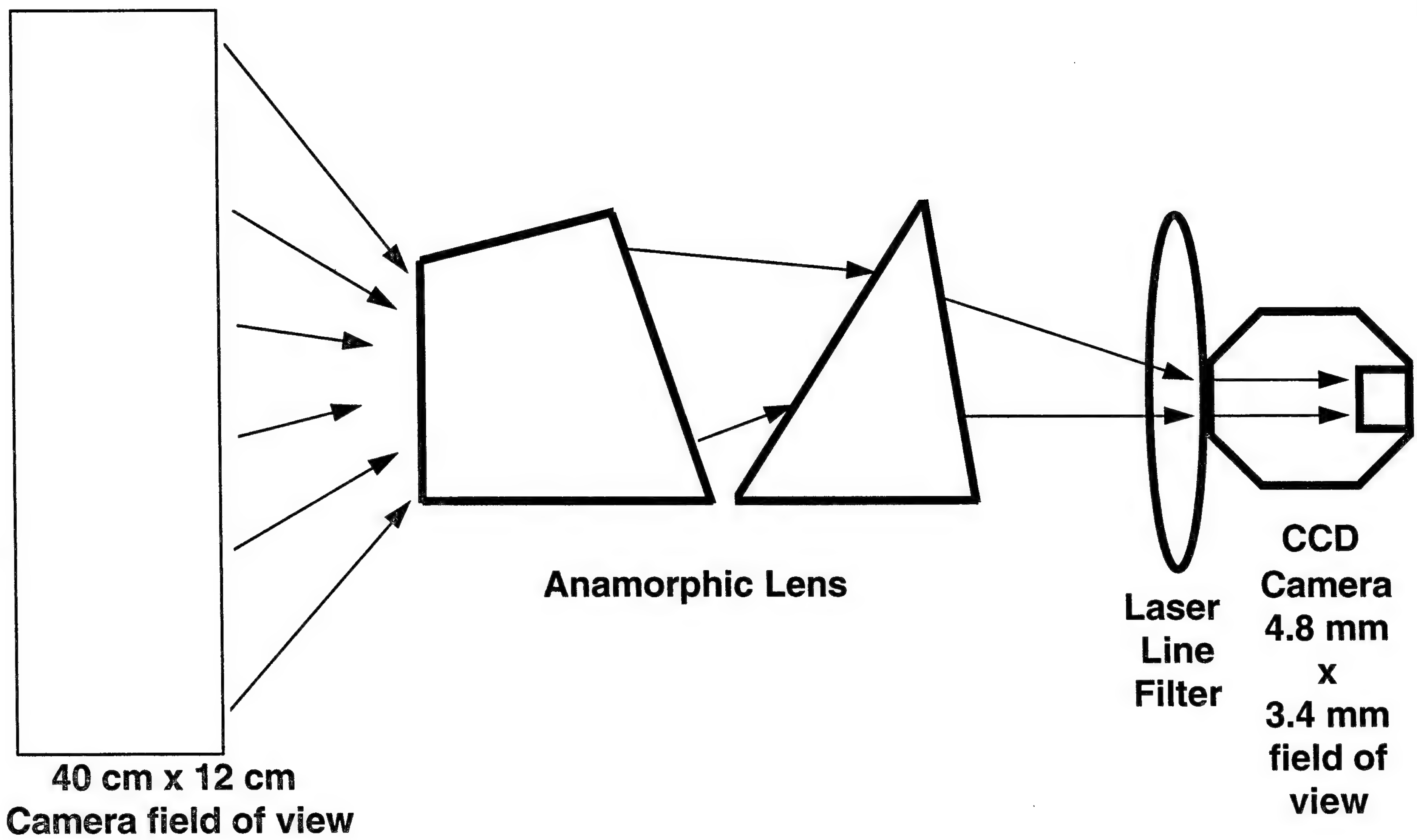


Figure 3, Anamorphic Lens System Configuration

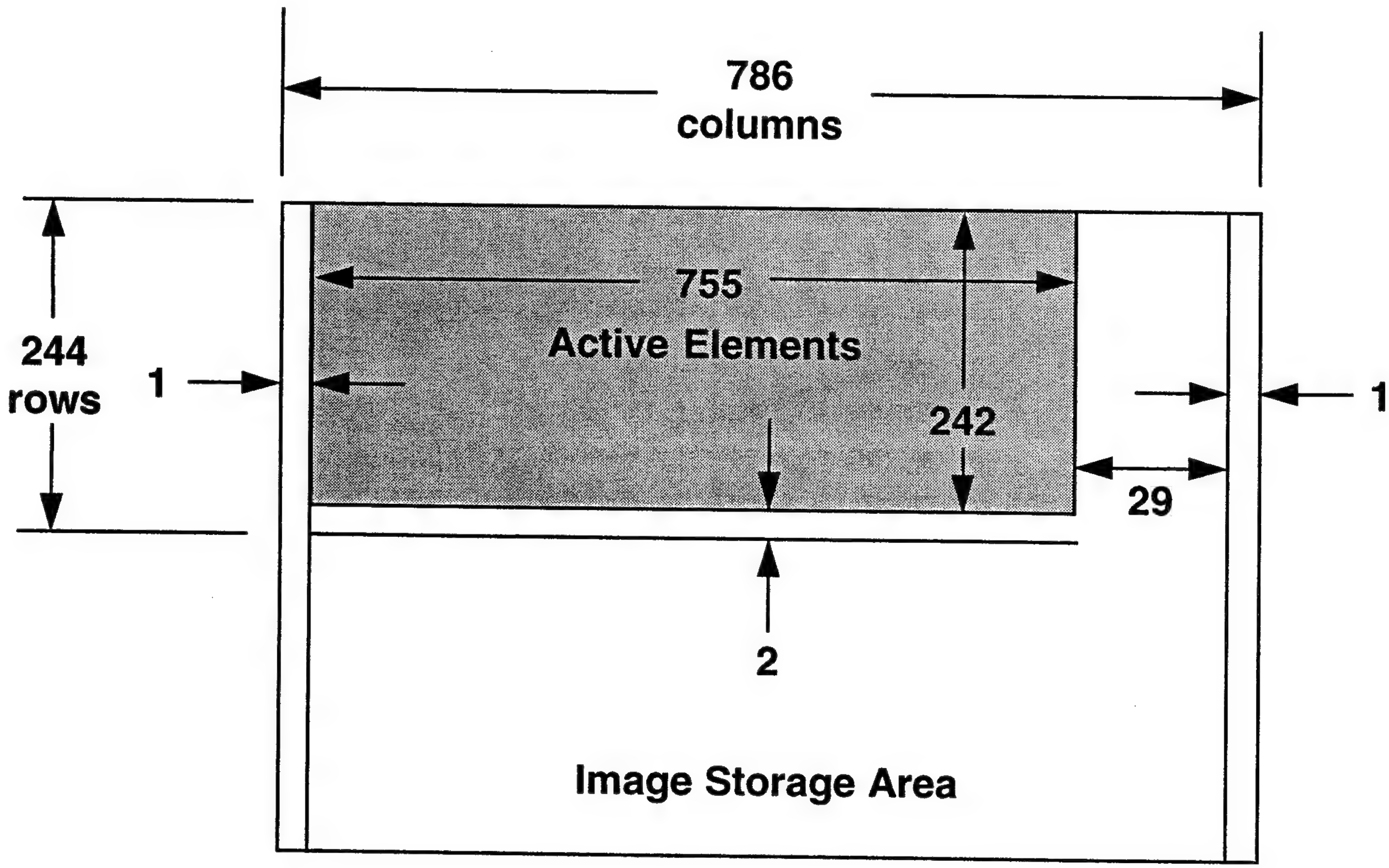


Figure 4, CCD Array Image Sensing Area

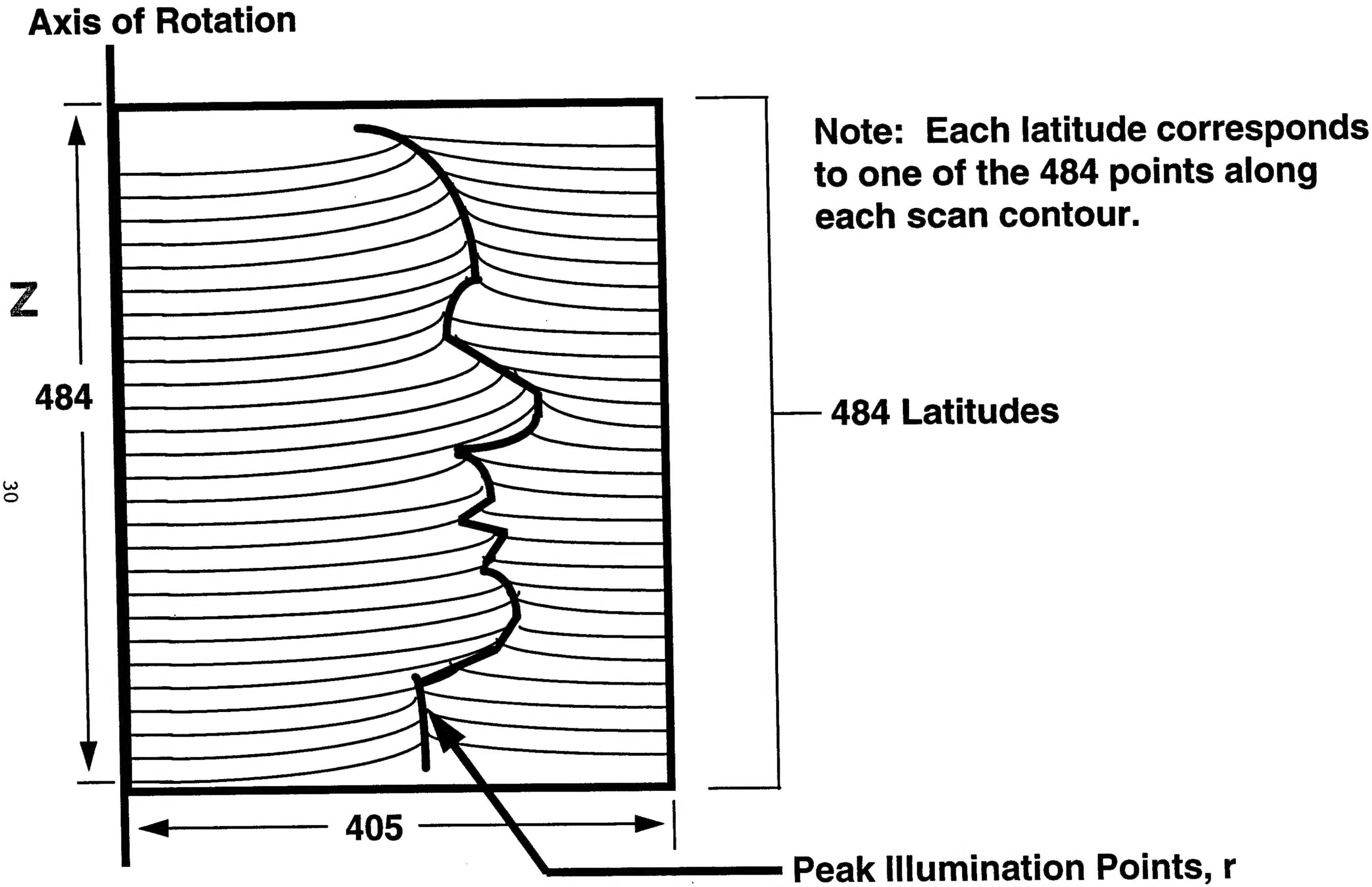


Figure 5, CCD Array (1 Image)

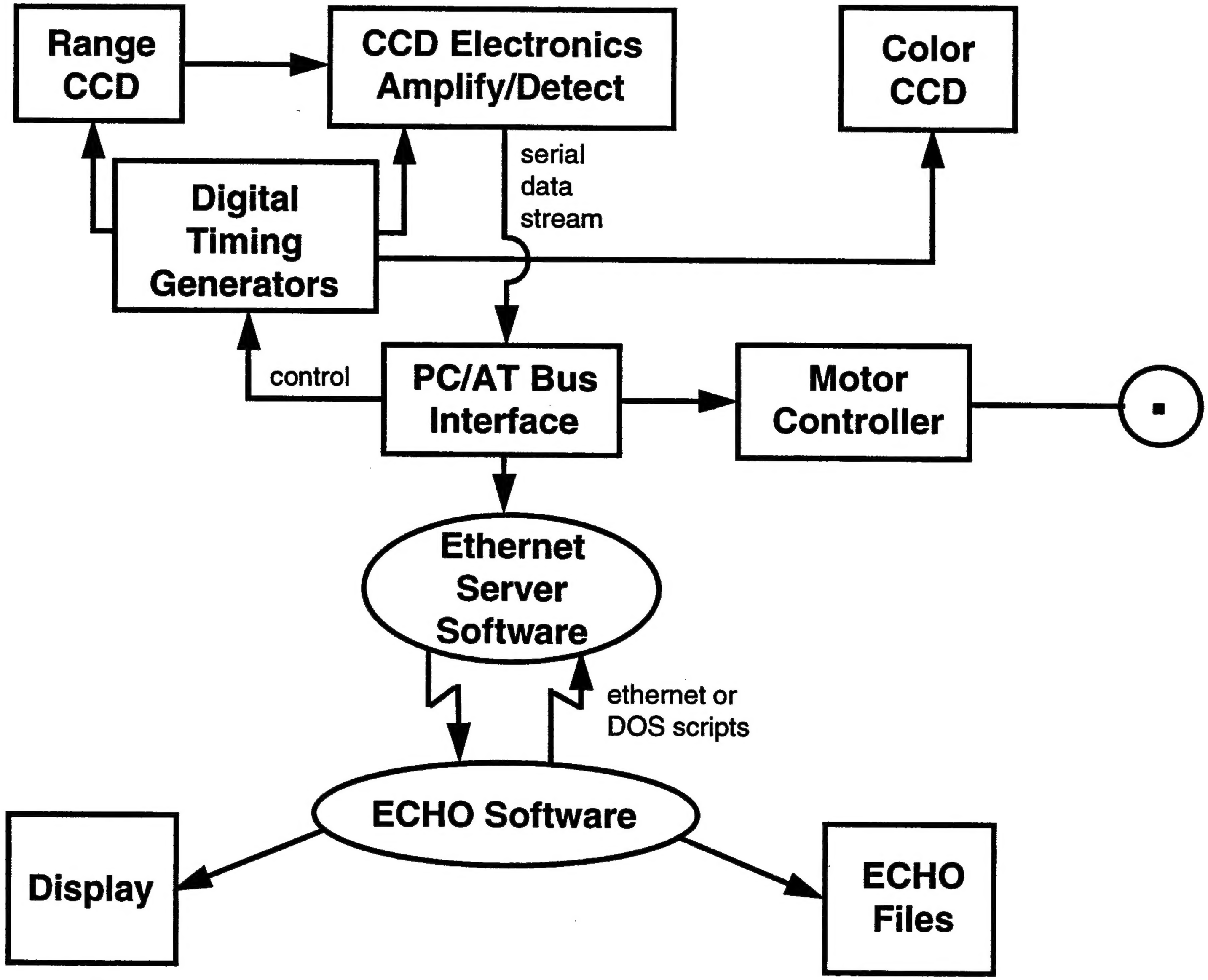
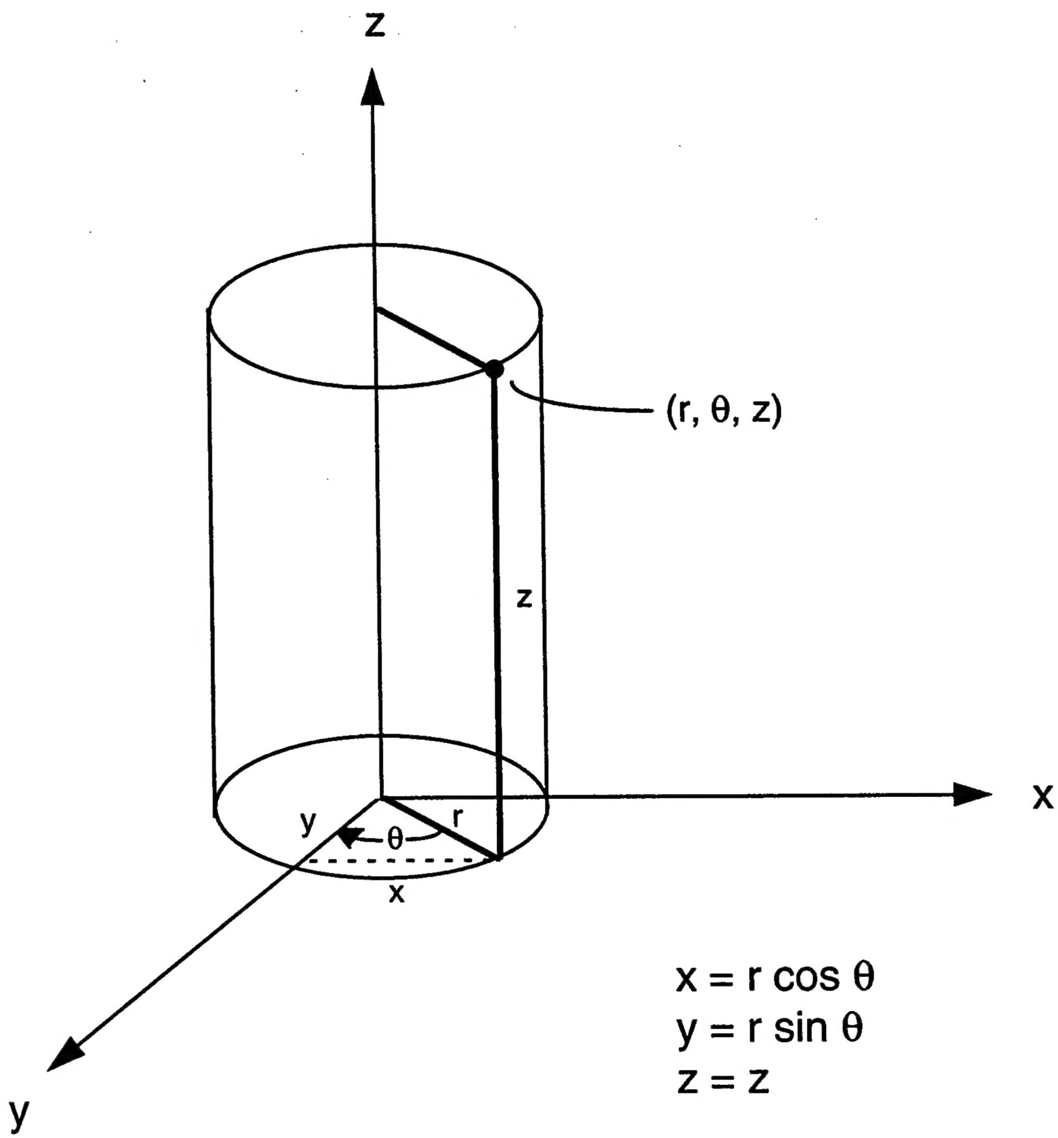


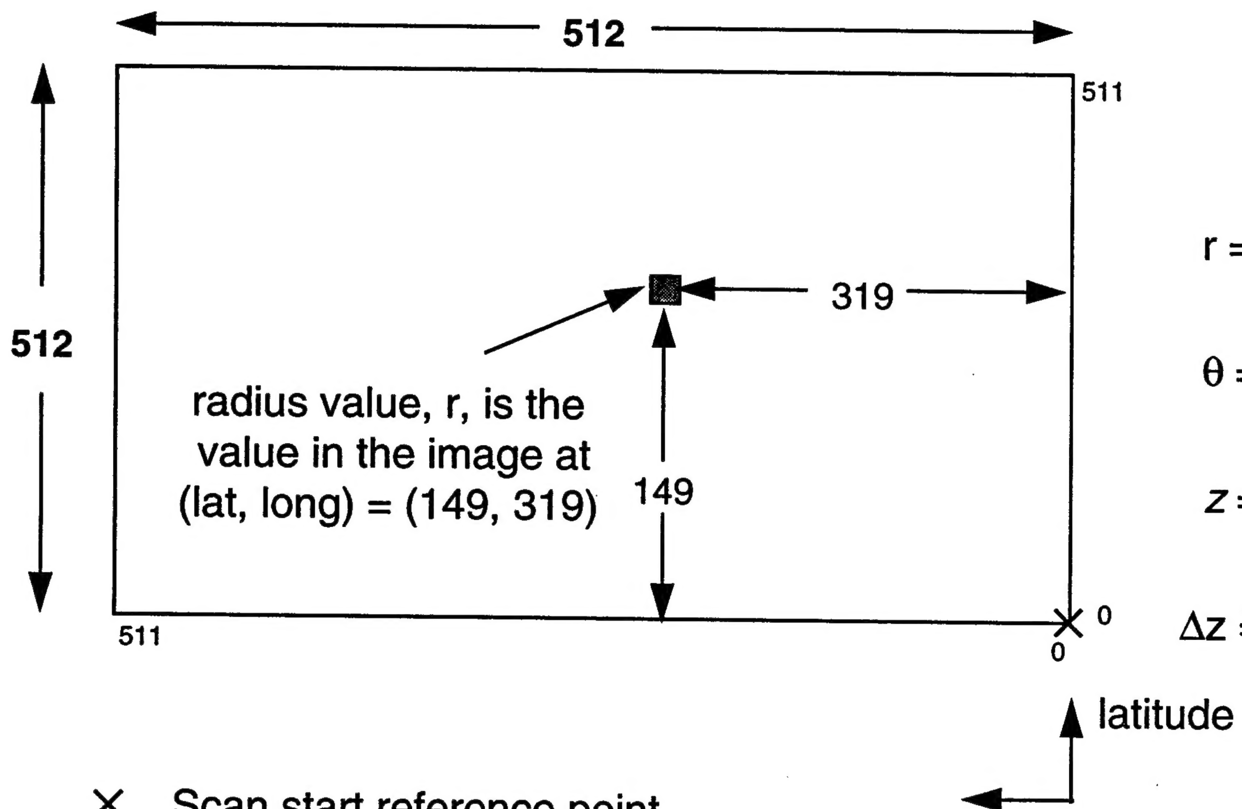
Figure 6, Digitizer Electronics Flow Diagram



$$x = r \cos \theta$$
$$y = r \sin \theta$$
$$z = z$$

Figure 7, Scanner Coordinate System

Range Data File



× Scan start reference point
(origin: latitude =0, longitude =0)

r = value in range data file

$$\theta = \frac{319}{512} \times 360^0 = 224^0$$

$$z = 149 \times \Delta z$$

$$\Delta z \cong \frac{400\text{mm}}{512\text{ lat}} = 0.781 \text{ mm/lat}$$

Figure 8, Conversion of Range Data to Cylindrical Coordinates

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